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REPORT

DIGITAL VIDEO: subjective assessment of an experimental Wyner-Ash error corrector

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION December 1974

BBC RD 1974/41
UDC 621.376.56
621.397.2

DIGITAL VIDEO: SUBJECTIVE ASSESSMENT OF AN EXPERIMENTAL WYNER-ASH ERROR CORRECTOR

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Summary

The performance of an experimental digital video error corrector is assessed and is found to provide satisfactory protection for error probabilities up to about 10^{-5}*, as predicted. A Wyner-Ash (8, 7) convolutional code is employed which requires a relatively small increase in the transmitted bit-rate. The error corrector is designed to correct random digit errors that occur in digital video transmission channels, and also to provide some measure of short burst-error protection. It would thus be effective with certain transmission codes which can produce multiple errors in the decoded output of the receiver when a single digit is in error in the transmission code.*

Issued under the authority of

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

December 1974
(EL-95)

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DIGITAL VIDEO: SUBJECTIVE ASSESSMENT OF AN EXPERIMENTAL WYNER-ASH ERROR CORRECTOR

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1. Introduction

It is envisaged that the transmission of video signals by digital methods will require some protection against digit errors. The exact nature of the errors likely to be introduced in the transmission path is not known with any degree of certainty at the present time but on some types of link at least, there will normally be a higher probability of random single digit errors than any other form of errors. However, some transmission codes (HDB-3 for example[1]) can cause the decoded data stream to contain several digit errors occurring within a certain limited period after a single digit error occurred in transmission. Thus a simple form of coding is then required which will give the digital data both single-error protection and short burst-error protection.

Bit-rate is at a premium and the most efficient code that will detect and correct random single digit errors, and which can be fairly simply instrumented, would appear to by a Wyner-Ash convolutional (recurrent) code.[2,3] Short burst-error protection can be provided by coding the data in parallel streams and then suitably interlacing these streams for serial transmission. Burst-errors of less duration, in terms of number of digits, than the number of parallel streams produce no more than one digit error in any one of the received parallel streams, and these are then corrected by the single-digit error-correcting code.

Longer burst-errors (typically caused by electrical discharges, switching, and other transient phenomena), are likely to be less frequent, and a different form of protection is required. It would not be practicable to design an error-correcting code to cope with such situations, and for video a better solution is likely to be provided by detecting an 'overload' of the simple error protection system, and then switching to some form of error concealment system (see Reference 4 for example).

This report describes the performance of an experimental Wyner-Ash error corrector, the detailed basis and design of which is described in Reference 5.

2. Wyner-Ash (8, 7) convolutional code

2.1. General

A Wyner-Ash code was chosen which can correct any one error occurring within a group of 32 digits (the code constraint length), by the addition of one parity bit for every seven data bits;[5] the eight bits comprise a 'block' and the code may be described as an (8, 7) code. The form of the code is illustrated in Fig. 1, applied to a single data* stream. Each parity bit checks all the bits in its own block (including itself), plus certain of the bits in each of the three preceding blocks, as shown. The parity bit is calculated to maintain an odd number of '1's in the 20 bits included in the check. The decoder re-calculates the parity bits in the same manner as the coder, and also stores the received parity. Comparison of the two parity bit streams should yield no differences, but if a transmission error occurs the parity check for the block in which the error occurred will fail, and providing that there are no other errors within the next three blocks, the subsequent three parity checks will indicate which bit was received in error. This can be corrected by inversion of the erroneous bit, and the parity violations are then nullified to prevent error propagation.

This Wyner-Ash (8, 7) code is likely to provide a near-optimum trade-off of error-correcting ability against increased bit-rate[5] in many applications, but the choice may depend on the expected transmission error rate. The (8, 7) code requires an increase of about 14% in the bit-rate, and the theoretical improvement in output error probability is shown in Fig. 2. The larger the code constraint length for any given random error probability the greater is the probability of two errors occurring within it (and consequent failure of the protection system), but the less is the increase in the transmitted bit-rate. In addition, the larger the code constraint length, the larger also is the storage capacity required in the coder. The compromise is illustrated by comparison with the output error probabilities of Wyner-Ash (4, 3) and (16, 15) codes, also shown in Fig. 2. The theoretical derivation of these curves, including the assumptions made, is given in Reference 5.

2.2. Implementation of the code in the digital video signal

Observation of the results of earlier tests using an error concealment technique[4] indicates that not all the bits of an 8-bit pulse-code modulation (p.c.m.) video signal word require protection because of their differing signifi-

* The term 'data' in this respect refers to 'wanted information', i.e. that describing the source-coded digital video signal.

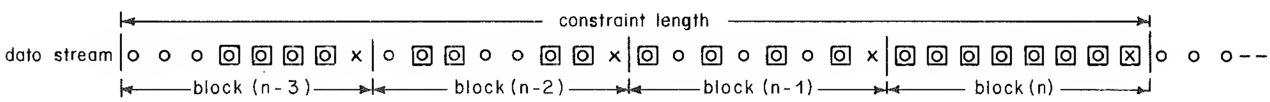


Fig. 1 - The Wyner-Ash convolutional code

o data-bits   x parity bit   parity bits ☒ check data bits ▣

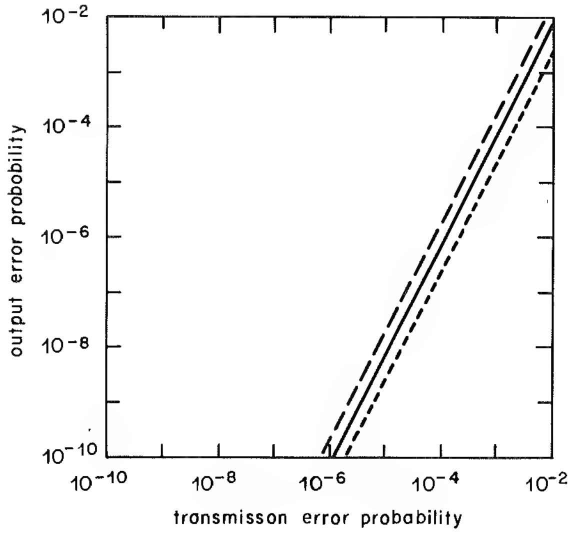


Fig. 2 - Theoretical performance of Wyner-Ash convolutional codes

— — — — (16, 15) code (7% increase in bit rate)
———— (8, 7) code (14% increase in bit rate)
- - - - - - - (4, 3) code (33% increase in bit rate)

cance. In applying the experimental Wyner-Ash error correcting coder and decoder (codec) to such a video signal it was arranged to provide protection in up to the first four most significant bits (m.s.b.s) of the digital video signal. Since only half of the digital data is protected, the additional parity information need only cause an increase in the bit-rate of about 7% when the data is serialised for transmission, if suitable grouping is chosen for the parity bits.

The scheme employed is shown in Fig. 3. The code is applied separately to the four m.s.b.s in parallel, and on serialising the data, the inserted parity digits are collected to form 8-bit parity words, one before every 14 data words. Each data word is sent sequentially, such that protected bits of a given significance from the four m.s.b. streams actually occur eight digits apart. Thus a burst-error of up to eight digits in length would only affect one bit of each of the parallel data streams, and, assuming that single digit errors in the four least significant bits (l.s.b.s) are not significant, the correction system would operate satisfactorily. Unfortunately, however, if the burst-error occurred in the parity word, only burst lengths of up to four digits would be guaranteed to be corrected, since parity bits from the same parallel bit streams occur only four digits apart. This is the penalty paid for regrouping the parity digits such that the transmitted bit rate is reduced from 14% higher to only 7% higher than the unprotected data rate.

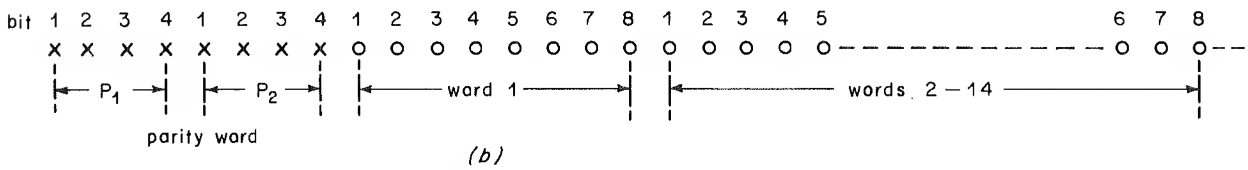
In order to determine the performance of the codec, a series of experiments was conducted, operating the codec on a simulated transmission channel into which random errors could be injected at a controllable rate. The system was assessed using pulse-code modulation (p.c.m.), a differential pulse-code modulation (d.p.c.m.), and a hybrid differential pulse-code modulation (h.d.p.c.m.), i.e. p.c.m./d.p.c.m.[8] A detailed description of the arrangements is contained in the next Section, while a summary of the differential coding arrangment is given in Section 7.2 of the Appendix.

3. Experimental arrangement for assessing the error corrector

Fig. 4 shows a block diagram of the arrangement used for the tests. This arrangement is similar to that used in a previous investigation[4] except that the error signal generator has been modified to provide a more truly random output by using a twin shift register approach,[6] (see Appendix, Section 7.1). Error rates up to 1 in 10^3 were obtainable with a minimum spacing between errors of two digits.

word	1	2	3	4	5	6	7	P_1	8	9	10	11	12	13	14	P_2	15	16	17	
bit 1	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	x	o	o	o	---
2	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	x	o	o	o	---
3	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	x	o	o	o	---
4	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	x	o	o	o	---
5	o	o	o	o	o	o	o		o	o	o	o	o	o	o		o	o	o	---
6	o	o	o	o	o	o	o		o	o	o	o	o	o	o		o	o	o	---
7	o	o	o	o	o	o	o		o	o	o	o	o	o	o		o	o	o	---
8	o	o	o	o	o	o	o		o	o	o	o	o	o	o		o	o	o	---

(a)



(b)

Fig. 3 - Coding scheme applied to digital video signal

o data bit x parity bit

(*a*) 8-bit digital video signal coded in parallel form (*b*) 8-bit digital video signal re-arranged in serial form

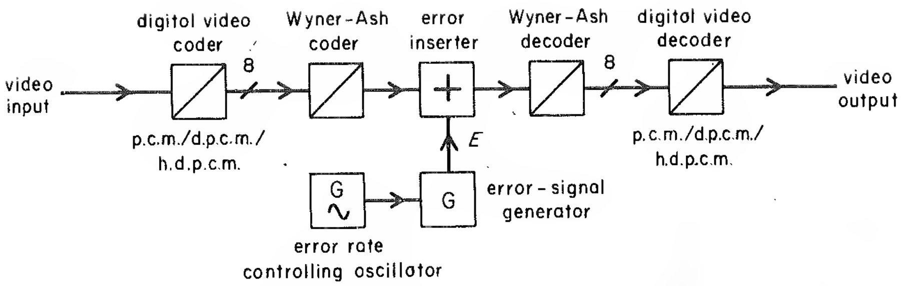


Fig. 4 - Arrangement for assessing Wyner-Ash error corrector

Each error pulse produced by the error generator could be used to affect a single data-digit or a continuous burst of up to 20 digits, and the errors could be inserted as data complements ('0' changed to '1' and vice-versa), all set-to-'1's (white errors), or all set-to-'0's (black errors).

The digital video codec provides 8-bit p.c.m., 6-bit d.p.c.m., or 6-bit h.d.p.c.m. samples in parallel form, and operates at a sampling rate of 13·3 MHz. It consists of an 8-bit linear p.c.m. codec, described in a previous report,[7] and a codec which converts 8-bit p.c.m. signals to 6-bit d.p.c.m. or h.d.p.c.m. signals, similar to that described in Reference 8, which may be selected as desired (see Appendix, Section 7.2). The Wyner-Ash codec accepts a parallel input, provides parity protection on the four m.s.b.s of the input signal and gives an output in 8-bit serial format at about 114 Mb/s. By setting manually-operated switches the decoder is capable of applying error correction on any of the four protected parallel data streams, and outputs the received video data in 8-bit parallel form for the normal digital to analogue conversion process. The two l.s.b.s of the codec are not used with the 6-bit d.p.c.m. and h.d.p.c.m. transmissions.

In a practical d.p.c.m. or h.d.p.c.m. link the serial bit-rate would obviously be less than 114 Mb/s, and the coder would send only 6-bit data samples. However, since the errors are applied in serial form, the effective error-rate in each parallel channel is equal to the serial error-rate, and so code performance can still be meaningfully evaluated from the tests to be described.

4. Subjective tests

4.1. Procedure

The video signal obtained from the output of the digital video system shown in Fig. 4 was displayed on a high-quality 22-inch colour monitor under CCIR viewing conditions.[9] Error-free synchronising pulses were fed to the monitor to avoid disturbances of the overall picture geometry produced by high error rates, since these were irrelevant to the present purpose as they could, in normal circumstances, be substantially removed by suitable processing techniques.

A PAL 625-line colour video signal (System I) was obtained from a 35 mm colour-slide flying-spot scanner containing a slide of which a monochrome version is shown in Fig. 5. This slide has been used in previous subjective assessments of picture quality and is known to provide a scene sensitive to digital errors.

Fig. 5 - Monochrome version of slide used in tests

Each test consisted of 30 exposures of the picture with differing error-rates, error-types, and degrees of error protection, arranged in random order, on each of the three digital source codes, i.e. p.c.m., d.p.c.m. and h.d.p.c.m. Seven engineers, all experienced in assessing picture quality, were asked to grade each exposure according to the EBU 6-grade impairment scale shown below.

EBU 6-grade impairment scale

Grade	
1	Imperceptible (no impairment)
2	Just perceptible (negligible impairment)
3	Definitely perceptible but not disturbing (slight impairment)
4	Somewhat objectionable (marked impairment)
5	Definitely objectionable (severe impairment)
6	Unusable

The additional comments in parentheses were added to avoid slightly confusing aspects of the normal scale with the type of impairment caused by digital errors. For example, single errors separated by long intervals might be 'definitely perceptible' at their moments of occurrence, yet be so infrequent that they constitute too trivial an impairment to merit the comparatively adverse assessment implied by grade 3.

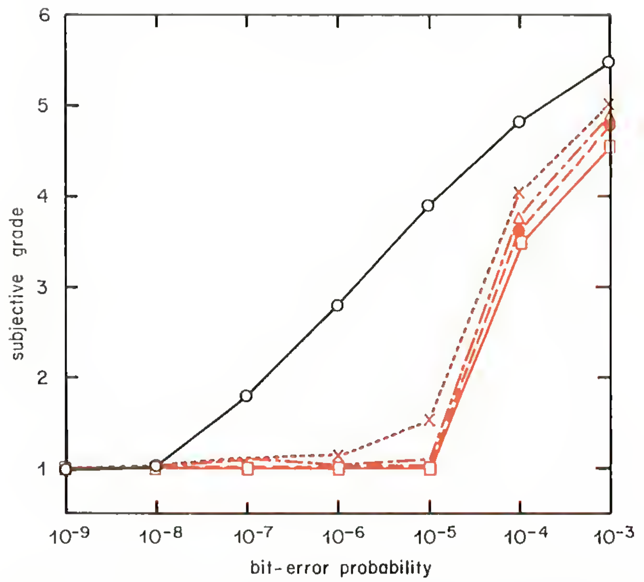


Fig. 6 - Performance with 8-bit p.c.m. signal and single 'bit-invert' errors

Unprotected
bit 1 protected
bits 1, 2 protected
bits 1, 2, 3 protected
bits 1, 2, 3, 4 protected

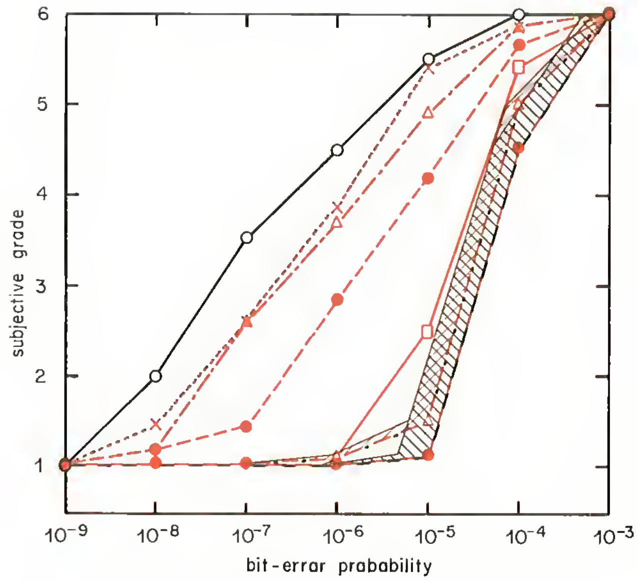


Fig. 7 - Performance with 6-bit d.p.c.m. and single 'bit-invert' errors

Unprotected
bit 1 protected
bits 1, 2 protected
bits 1, 2, 3 protected
bits 1, 2, 3, 4 protected
bits 1–4 protected, 5 correct) showing area of probability for
bits 1–4 protected, 5 and 6 correct) true 5 and 6 bit Wyner-Ash) protection.

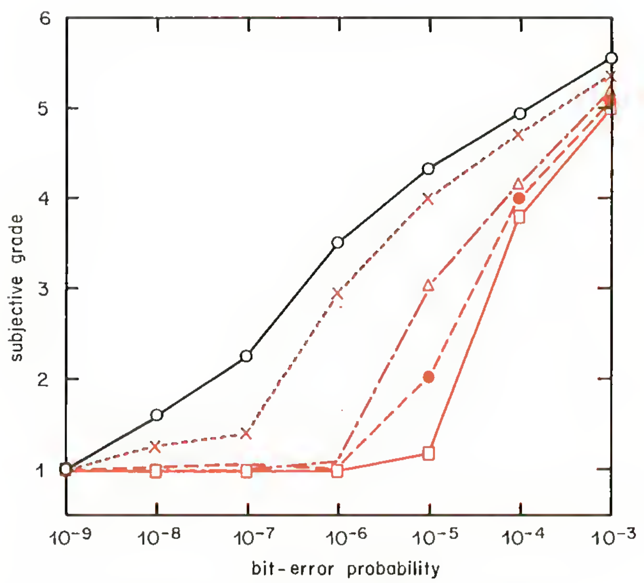


Fig. 8 - Performance with 6-bit h.d.p.c.m. with single 'bit-invert' errors

Unprotected
bit 1 protected
bits 1, 2 protected
bits 1, 2, 3 protected
bits 1, 2, 3, 4 protected

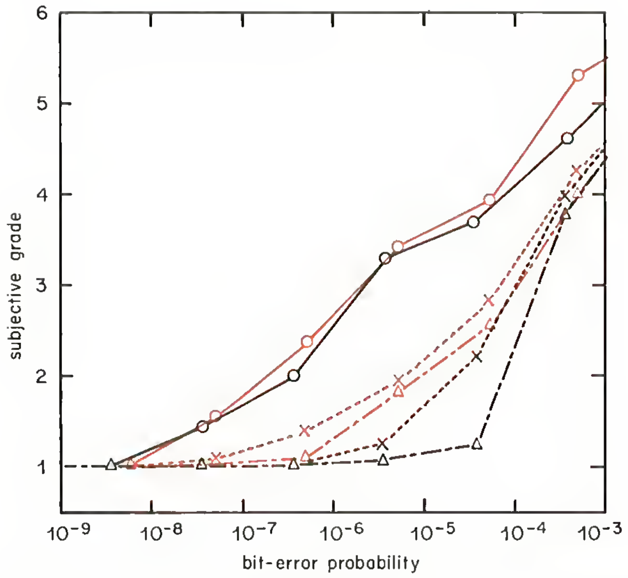


Fig. 9 - Performance with 8-bit p.c.m. with 4 and 5 bit 'white' error bursts

Unprotected
bit 1 protected
bits 1, 2, 3, 4 protected
} 4-bit burst errors

Unprotected
bit 1 protected
bits 1, 2, 3, 4 protected
} 5-bit burst errors

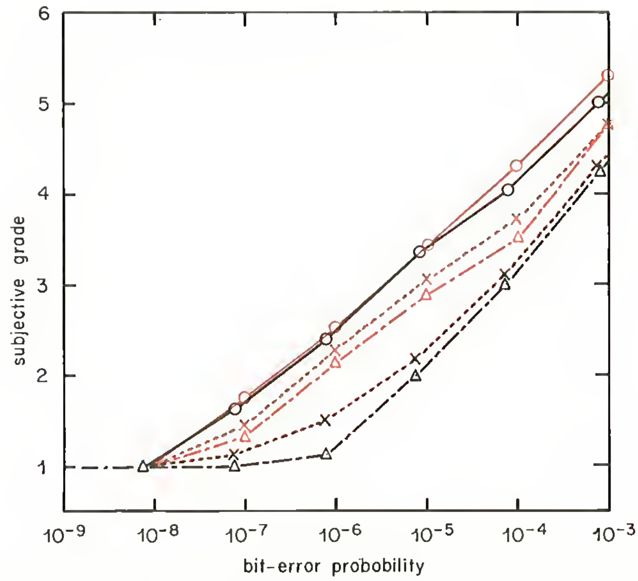


Fig. 10 - Performance with 8-bit p.c.m. with 8 and 9 bit 'white' error bursts

Unprotected
bit 1 protected
bits 1, 2, 3, 4 protected
} 8-bit burst errors

Unprotected
bit 1 protected
bits 1, 2, 3, 4 protected
} 9-bit burst errors

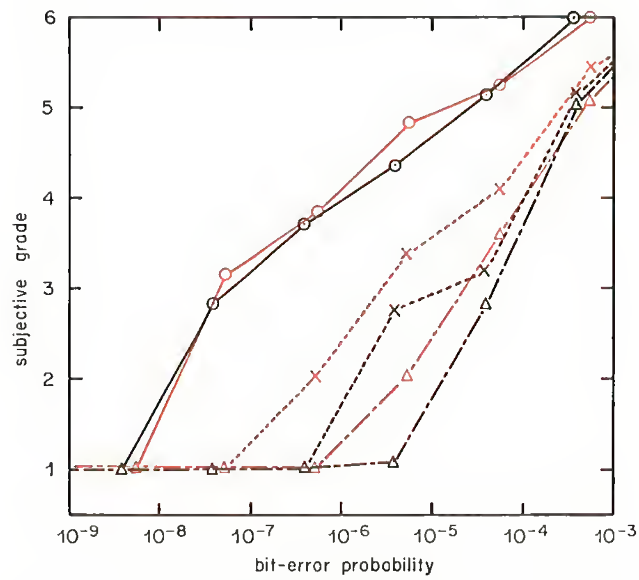


Fig. 11 - Performance of 6-bit d.p.c.m. with 4 and 5 bit 'white' error bursts

Unprotected
bits 1, 2, 3, 4 protected
bits 1, 2, 3, 4 protected, bit 5 correct
} 4-bit burst errors

Unprotected
bits 1, 2, 3, 4 protected
bits 1, 2, 3, 4 protected, bit 5 correct
} 5-bit burst errors

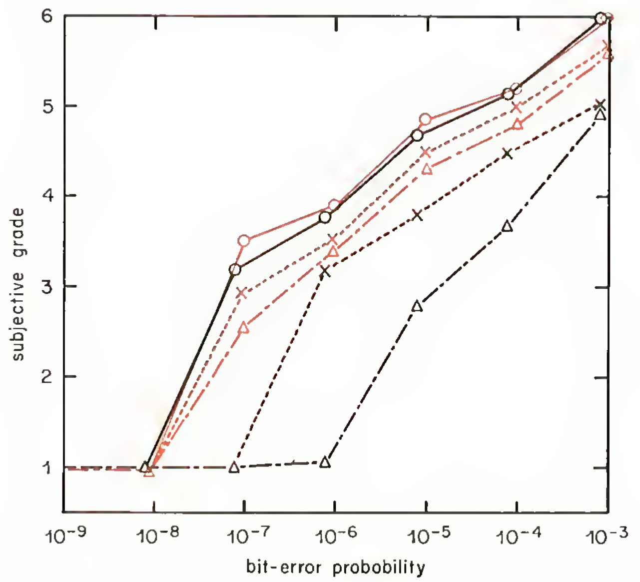


Fig. 12 - Performance of 6-bit d.p.c.m. with 8 and 9 bit 'white' error bursts

Unprotected
bits 1, 2, 3, 4 protected
bits 1, 2, 3, 4 protected, bit 5 correct
} 8-bit burst errors

Unprotected
bits 1, 2, 3, 4 protected
bits 1, 2, 3, 4 protected, bit 5 correct
} 9-bit burst errors

In analysis of the results of the subjective tests a mean grade of 1·5 is taken to be the limiting criterion for acceptable picture quality, and error probabilities are quoted at this grade.

4.2. Results

4.2.1. General

Results for these tests are presented in Figs. 6 – 12. The relative positions of the curves on each graph should be considered as fairly representative, but it should be noted that their absolute position is subject to variation from test to test. Typical standard deviations of results were half of one grade within a single test, but an overall shift in the grading scale of up to half of one grade could be observed between different tests. Thus comparisons between figures should be made with caution.

4.2.2. Single 'invert' errors

The effect of random single digit errors on 8-bit linear p.c.m. is shown in Fig. 6. Protection of only the most significant bit (bit 1) is seen to have a dramatic effect, and little further improvement is obtained from protecting more than the first two m.s.b.s (bits 1 and 2). A break-point between error probabilities of 10^{-4} and 10^{-5} occurs using the code, and this is in agreement with the theoretical prediction. At the break-point picture quality is some three grades better than the unprotected version.

Fig. 7 shows the performance with 6-bit d.p.c.m. Unprotected errors are visible at an error probability one order of magnitude less than that for 8-bit p.c.m., and even four-bit code protection is not as effective as one-bit protection on p.c.m.; d.p.c.m. is much more sensitive to errors than p.c.m. because single errors are extended across a whole line of the video signal, d.p.c.m. prediction being reset for each line of picture.

In order to simulate the performance of Wyner-Ash error correction on five or all six bits of the d.p.c.m. signal, provision was made for bits 5 and 6 of the parallel signal to by-pass the serial error-inserting path, such that these bits were always received correctly. This means that for bit 5 correct, or bits 5 and 6 correct, the actual overall error probability in the video signal is reduced to $^5/_6$ or $^2/_3$, respectively, of the serial error probability, although of course the error probability on bits 1 – 4 is the same as the serial error probability. Also, because half of the parity bits protecting data bits of significance 1 and 2 is conveyed in bit streams of significance 5 and 6 (due to parity regrouping, see Fig. 3) a slight improvement in the operation of the Wyner-Ash code may be expected. The actual results obtained are thus plotted as an upper-bound to the improvement expected of true five or six bit Wyner-Ash code protection, and the shaded regions indicate the probable areas in which the true results would lie. It would then appear that 5-bit protection would probably just provide a satisfactory output for error probabilities up to 10^{-5}, although it would probably be no more difficult to protect all six bits.

Hybrid d.p.c.m. combines the bit-rate reducing advantages of d.p.c.m. with some of the error resistance of p.c.m., and results for this mode of transmission are shown in Fig. 8. Since the error extension problem of d.p.c.m. is mitigated with h.d.p.c.m. the subjective impairment is greatly reduced so that, with an (8, 7) Wyner-Ash code, 4-bit error protection provides an acceptable output for error probabilities up to 10^{-5}.

4.2.3. 'White' burst-errors

A limited investigation of the performance of the codec with short burst-errors was carried out, using set-to-'1' ('white') burst errors of lengths 4 or 5 bits and 8 or 9 bits in the serial bit stream. These lengths were chosen to provide comparisons at the expected break-points in the burst-error correcting ability of the code, and 'white' bursts were used because it is known[4] that they give up to 1·5 grades more impairment than 'black' (set-to-'0') bursts; thus these results represent the minimum amount of burst-error protection obtainable.

Results for 8-bit linear p.c.m. are shown in Fig. 9 with error correction applied to bit 1 only, and bits 1 – 4. Note that the x-axis is scaled at 'bit-error probability' as opposed to 'burst-error probability'. Protection of 4-bit bursts is provided up to an error probability of 5 x 10^{-5} using 4-bit error correction, but is an order of magnitude less with only bit 1 protected. With 5-bit bursts, double errors will occur in the parity word, and the degradation is immediately apparent. Either 1- or 4-bit error protection then provides an acceptable output only up to an error probability of about 2 x 10^{-6}

Fig. 10 shows 8- and 9-bit burst-error performance, and with 8-bit bursts it is little different from that with 5-bit bursts shown in Fig. 9. With 9-bit bursts, however, there is little error protection provided with either bit 1 or bits 1 – 4, error correction operative. These bursts will always produce two errors in at least one bit stream and, unless they start in the latter half of a data word not preceding the parity word, two errors will occur in a protected bit stream. If the burst length is increased to 13 bits in length two (or more) errors will always be produced in all the parallel bit streams.

Similar results are shown for 6-bit d.p.c.m. in Figs. 11 and 12, showing the effect of 4-bit Wyner-Ash error protection, and 4-bit error protection plus bit 5 sent correctly. 4-bit protection gives an acceptable output up to a bit-error probability of 10^{-6} with 4-bit burst errors (Fig. 11), and protection extends to a bit error probability of 7 x 10^{-6} when, in addition, bit 5 is sent correctly. However, the protection afforded against 5-bit burst-errors is reduced by a factor of five, and Fig. 12 shows a similar degree of protection afforded up to 8-bit burst lengths, but 9-bit bursts render the protection scheme virtually useless.

Performance of 6-bit transmission codes under burst-error conditions might be expected to be marginally better using the 8-bit experimental codec than using a true 6-bit Wyner-Ash codec, because in the experimental arrangement the transmitted digits corresponding to the two data streams

of least significance are largely redundant, and only convey parity information (1 digit in 16). However, the curves presented in Figs. 11 and 12 are believed to give a reasonable indication of the expected performance of a true 6-bit Wyner-Ash codec.

No burst-error tests were conducted with h.d.p.c.m. but a quick assessment indicated a similar performance to that of 8-bit p.c.m. with bits 1 – 4 protected.

5. Conclusions

The experimental Wyner-Ash (8, 7) code error corrector has been shown to perform as predicted, and can provide correction of random single-digit errors with error probabilities of up to about 10^{-5}. Burst-error protection is seen to operate as expected, although the particular instrumentation employed only provides full protection with burst lengths up to 4 bits.

Using an (8, 7) code, it appears that protection of only the two most significant parallel bit streams is required using 8-bit p.c.m. source-coding, but with 6-bit d.p.c.m. at least five bits must be protected, and with h.d.p.c.m. four-bit protection is required. A summary of the performance of the Wyner-Ash (8, 7) code error corrector applied to the four most significant bits is contained in Fig. 13. It gives the range of bit-error probability over which the picture remains at grade 1·5 or better, with burst-lengths that are progressively less disturbing, reading from left to right, when protection is applied.

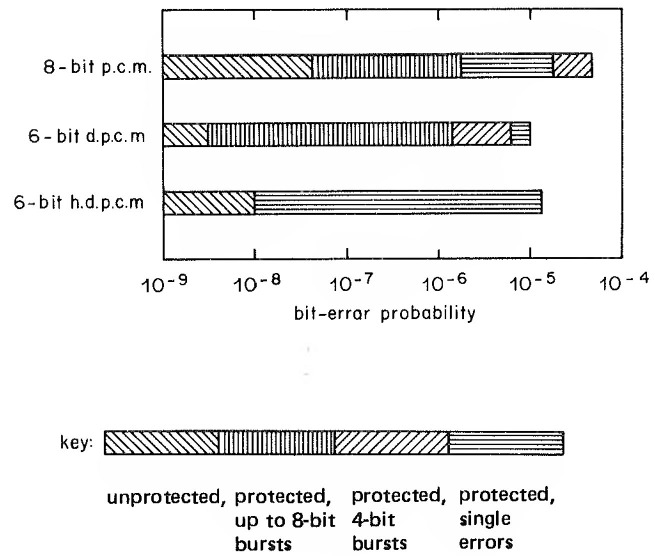


Fig. 13 - Summary of results of subjective tests at grade 1·5 impairment with bits 1 – 4 protected

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7. Appendix

7.1. Error signal generator

Clock pulses from a free-running oscillator are applied to a 25-stage shift register with feedback taken from the 22nd and 25th stages via an exclusive OR gate to the input of the first stage. With such a feedback system, the output of any stage of the shift register consists of a 'maximal-length' pseudo-random sequence of '1's and '0's, with a repetition time of $2^{25} - 1$ clock pulses (about 3 secs at a clock rate of 11 MHz). The mean time between '1's (or '0's) is two clock periods, and in order to increase this such that '1's may be used as randomly-occurring error pulses, outputs from a number of stages of the shift register are fed to an AND gate, the output of which is used as the error signal.[4] However, a more truly random output is obtained[6] by splitting the shift register into two, shifting pulses in opposite directions. Then by taking pairs of adjacent outputs from the various stages of the registers, and passing them into exclusive OR gates, the outputs obtained are less inter-dependent, and are used to feed the final AND gate. In practice a single shift register is retained and pairs of outputs are taken, one from each end of the register, working towards the centre of the register with successive pairs of outputs. The generator used in the tests described in this report has 13 feeds to the AND gate, 6 of which can be disabled in pairs to provide lower error rates for the same clock frequency. The latter determines the minimum time between errors, which is about 90 nS at a maximum operating frequency of 11 MHz. At all frequencies above about 7 MHz, no more than two consecutive bits in the parallel bit streams of the received data will have total error immunity, and this is considered satisfactory for testing the Wyner-Ash Codec. Error-rate versus clock-frequency graphs are given in Fig. 14.

7.2. 6-bit codec*

The 6-bit d.p.c.m./h.d.p.c.m. codec used in the experiments described in this report is essentially a digital transcoder which converts an 8-bit linearly-quantised digital video signal into a 6-bit non-linearly quantised signal, and vice-versa.

The p.c.m. signal is digitally processed to obtain a difference signal which indicates the change in level between every third previous sample.** The number of bits

* The 6-bit codec was designed by V.G. Devereux.

** For PAL signals the advantage of using third sample differences rather than successive ones is that the presence of colour subcarrier then has virtually no effect on the difference signal, when a sampling frequency close to thrice colour subcarrier frequency is used; as a result the colour subcarrier is encoded with 8-bit accuracy in low-detail areas of the picture.

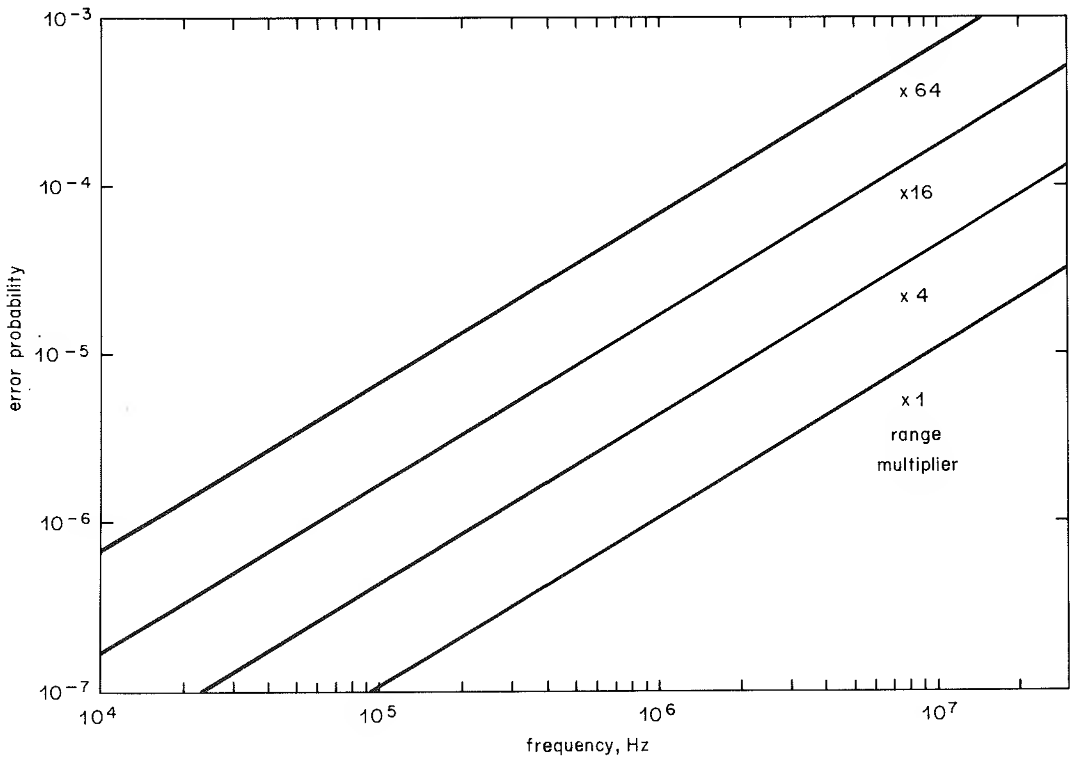

Fig. 14 - Error probability versus input clock frequency for error signal generator

required for the d.p.c.m. signal is reduced to six by passing the difference signal through a non-linear quantiser with only 64 output levels. The characteristic of this law (see Fig. 15) is such that small differences between samples are encoded with the same accuracy as in 8-bit linear p.c.m., but large differences are encoded less accurately, at worst with the same accuracy as in 5-bit linear p.c.m. The d.p.c.m. system requires that absolute p.c.m. values are sent from time to time in order to prevent the accumulation of quantising errors, and this is conveniently achieved in the line-blanking interval.

In the h.d.p.c.m. mode of operation the same non-linear quantiser is employed, but difference samples are only sent if their values lie within 32 output levels. If the difference lies outside this range a 5-bit p.c.m. sample is sent with a '1' added as the most significant bit to indicate that it is a p.c.m. value. In the decoder all p.c.m. samples received are decoded with the code '100' (half a 5-bit p.c.m. quantising step) inserted for the three least significant bits (l.s.b.s) of the 8-bit p.c.m. output signal, and thus any input sample to the coder having this code in the three l.s.b.s is also sent in the p.c.m. mode irrespective of the value of the difference signal.

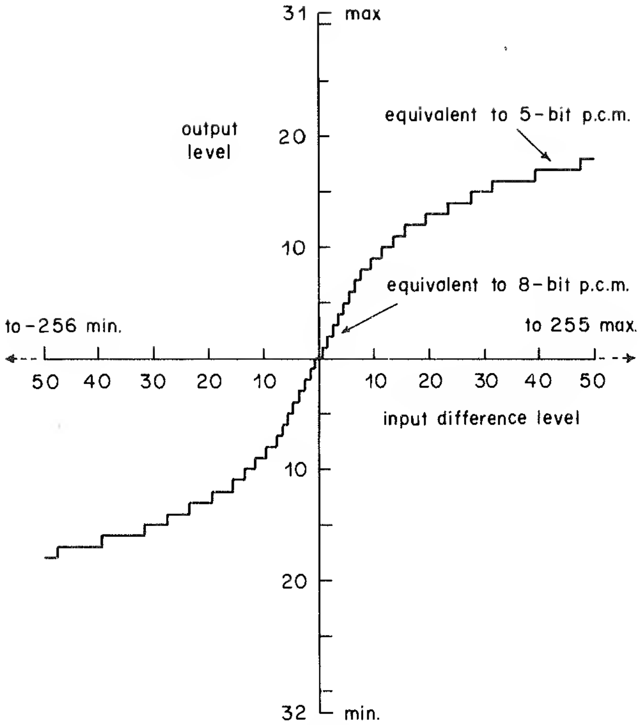

Fig. 15 - Characteristic of non-linear quantiser

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